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The sustainability indicators of power production systems

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ABSTRACT

One of the most important elements of economical and social development is to provide uninterrupted electric energy to consumers. The increasing world population and technological developments rapidly increase the demand on electric energy. In order to meet the increasing demand for sustainable development, it is necessary to use the consumable resources of the world in the most productive manner and minimum level and to keep its negative effects on human health and environment in the lowest level as much as possible. In this study, alignment of hydrogen fuel cells, hydroelectric, wind, solar and geothermal sourced electric energy systems, in addition to fossil fueled coal, natural gas and nuclear power plants, in respect to sustainability parameters such as CO_2 emission, land use, energy output, fresh water consumption and environmental and social effects is researched. Consequently, it has been determined that the wind and nuclear energy power plants have the highest sustainability indicators. The fuel cells that use hydrogen obtained by using coal and natural gas are determined as the most disadvantageous transformation technologies in respect to sustainability. This study contains an alignment related to today's technologies. Using of renewable energy resources especially in production of hydrogen, output increases to be ensured with nanotechnology applications in photovoltaic systems may change this alignment.

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1. Introduction

The electric energy demand that is one of the main components of the economical and social development continuously increases because of various reasons such as increase in population, urbanization rate, industrialization and abundances. The electric energy is directly correlated with vital elements for countries of today's world. These elements can be divided into four sub-titles of production, national income, health and education. It is almost impossible for countries that lack of electric energy to ensure positive developments in such parameters.

It is known that at least 1.6 millions people in world do not consume any electric. Besides, in some countries, there exist great differences between the poor and the rich in obtaining energy. Energy plays a very important role for the peace of world, in addition to its role being an element that effects development of a country. For this reason, the World's Energy Council has resolved to act with understanding of "energy for people, energy for peace". According to the forecasts of the International Energy Agency, the energy need of world will increase two times in 2020 when compared to 1997 [1]. To meet this demand, the world's states, mainly the developed countries, make "energy reforms" that aim to benefit from alternative energy resources and encourage energy savings, besides to increase energy investments [2]. On the other hand, there are powerful proofs that global warming negatively affects the natural life in increasing rates and it will threat the human life in the near future. This causes the environmental organizations to focus on using of fossil fuels in order to decrease emissions of carbon dioxide and other harmful gases in atmosphere. Electric energy is among the mostly questioned technologies with this regard [3,4].

2. Sustainability and electric energy production

According to the definition made by United Nations Environment and Development Commission, the sustainable development is "a development that can meet the needs of today's world without endangering the ability of future generations to provide their own needs" [5]. When we consider this expression, we understand that we must use the consumable resources of world in the lowest possible level. The coverage of the sustainability concept in respect to electric energy production can be summarized as "to increase the potential of electric energy production continuously, keep the waste materials resulting from that production in a level that can be cleaned in natural ways, keep the risks related to human health in the lowest possible level and to realize the energy production by using raw materials including environmental resources in the lowest possible level [6]. In short, the sustainable energy production that can be defined with the Green Energy concept aims to reduce to the lowest possible level the usage of natural resources, the harmful gas emission and usage of the electric energy production methods that cause wastes. In this manner, it will be contributed to the process of slowing down the global warming and climate changes as well as new long-term employment opportunities and more balanced economical development in the world will be ensured.

2.1. Sustainability parameters

According to the definition above, sustainable development is a complex fact depending on many variables. In Fig. 1, indicators that generally effect the sustainable development are given [7]. While some of these indicators are dominant in definite areas, some

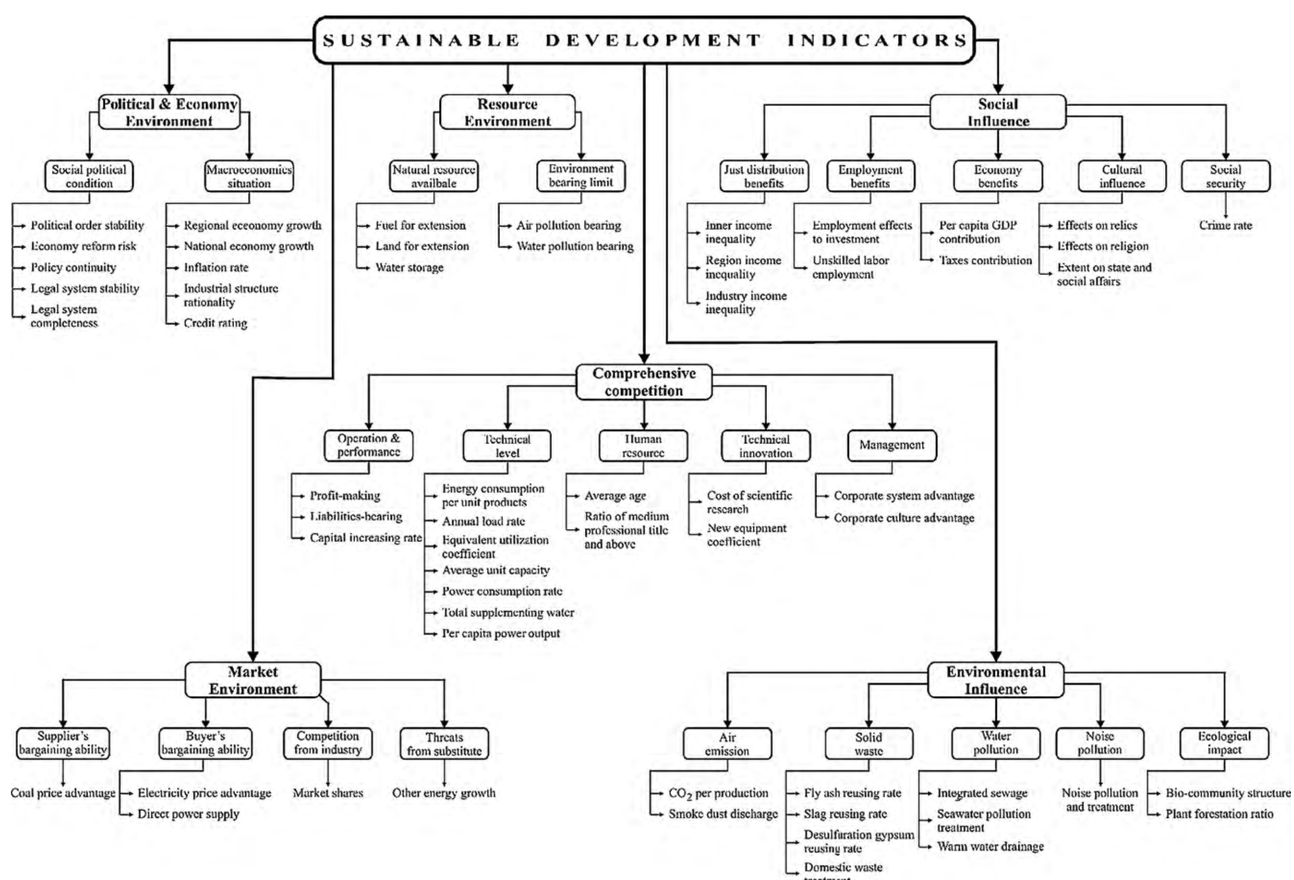


Fig. 1. Sustainable development parameters [7,8].

remain in the background. For instance, energy investments vary depending on various variables such as purchasing power, income distribution, education level, health standards, nutrition, biological variety, literacy rate, average life-span, work power and employment rates of that work power, accessibility opportunities for basic raw materials, credit note, etc. Effects of such sub-parameters on investments and their significance order vary depending on countries [8].

In publications made by international energy organizations, it is stated that in order the electric energy production technologies can be sustainable; they must be compatible with the 3A principle. The 3A principle contains the concepts of Accessibility, Availability and Acceptability. By considering this basic approach, we can summarize the sustainability parameters of an electric energy production technology as follows;

- The unit price of produced energy is an important factor that determines sustainability. Production technologies that are impossible to use economically cannot be sustainable.
- Especially, the sera gas emission amount is one of the most basic parameters that considered in sustainability analysis of an electric energy system.
- Availability and amount of resources used by each technology must be considered.
- To make a meaningful comparison, energy transformation output must be known. Technologies that are accepted as productive will be the systems that contain simpler production procedures and require lesser capital and operation cost. The low productive production technologies may have significant contribution in development of technology and realization of new discoveries.
- The land amount used by production technologies per unit energy is an important sustainability indicator. The renewable energy technologies, mainly hydroelectric systems, have to compete against to claims that they frequently use and destroy agricultural lands and give harm to biological variety.
- Water consumption is especially important in areas with arid climate. Today, many areas have water problems and supporting of energy production technologies with high water consumption and evaporation rates is not sustainable.
- Correct definition of current technologies will enable their risks on human life and the resulting long and short-term problems can be expressed clearly and be more understandable and easily acceptable. In this manner, objections to be made by the public may be decreased [9,10].

3. Factors effecting the development of alternative electric energy resources

The term of alternative energy resources is mostly used in same meaning with the renewable energy resources. However, hydrogen fueled cells and nuclear energy systems must be included in this term. So, the term of alternative energy resources express more comprehensive scope. There are very important success factors that encourage development of alternative energy resources, as well as disadvantages that may prevent such development. We can group the said success factors and obstacles under four main titles; perceptual, politic, legal and financial. Characters of these factors vary depending on development levels of countries.

3.1. Perceptual factors

The biggest perceptual disadvantage of alternative energy resources is that they are generally in position of complementary energy resource except the nuclear systems. These technologies are considered as new, of which success has not been proved sufficiently, installation and operation costs are high and on which research and development activities are permanently carried out. Besides, it is widely thought that they are the resources that make small scale, dispersed, instable production and do not have the ability to provide sustainable energy. These disadvantages are more highlighted in developing countries. These resources are perceived as complex systems that can only be used by the rich people and difficult to operate. Especially, budgets of poor countries hardly meet the first investment costs. Generally, they are the technologies far from being a solution to big energy problems of such countries. Nuclear power stations are perceived very pessimistically because of radioactive wastes and Chernobyl accident.

Contrary to the above said perceptual obstacles, continuous increase in energy needs, countries that do not want to make electric energy production depended on only one resource strategically and knowing how important to use national resources are the important success factors for the alternative energy systems. Besides, public opinion pressures about decreasing of dependency on fossil fuels, the society becoming more conscious about importance of clean and environment friendly energy resources and perception that such resources decrease the security risks ensure significant advantages. While the public opinion pressures sensitive to environment are more effective in developed countries, usage of domestic resources and expectation that foreign capital will be attracted to the country in this way are dominant in developing countries [1].

3.2. Political factors

In general, the energy market faces with some obstacles because of scarcity of comprehensive and harmonized policies. In many countries, there are unstable political structures that provide financial support preferentially to fossil energy resources. On the other hand, main policies still do not care about the social-environmental effects of fossil fuels. Contributions of clean and environment friendly renewable resources are being ignored. Rearrangement of energy market of developed countries is generally focused on non-interference. This attitude gives freedom to the private sector but have features preventing the development of renewable resources. In developing countries, obstacles in front of the alternative energy systems result from the structure of domestic energy system. Rapid development desire directs governments towards taking of nontransparent and open-ended decisions far from supporting the private sector. This approach causes unsustainable and irregular infrastructure developments in general and more importantly, production of policies that can be changed rapidly and are depended on central management. As a result of these short-term policies, besides to their negative impacts on environment, numerous fossil fueled power stations that are depended on importation of expensive fuels are installed in a manner distributed to many regions of a country, rather far distance to each other.

Climate change, taxation, encouragement and green protection certificate applications and enforcing of alternative energy policies by being planned are political advantages in front of us. Policies in developed countries to distribute the power energy equally to each region and political attitudes in developing countries to supply energy to rural areas from domestic resources independently from the network of country and to consider technology and knowledge transfer from development countries are the factors that increase the success chance of alternative energy resources [1,9].

3.3. Legal factors

Upon legal regulations made in developed countries recently, especially in a manner encouraging the renewable energy

resources, a little progress has been made. However, some developed countries, besides to developing countries, have not enforced transparent laws on energy yet. Meanwhile, laws on environment are insufficient. Existing laws are not being applied properly. The developed countries present legal obstacles under various reasons on sharing of authority in energy field.

Arrangements made by international credit companies and financial institutions to increase the environmental support, legal regulations and laws encouraging use of renewable resources and basic legal regulations supporting the private sector make important contributions in spreading of such resources.

3.4. Economic factors

Conventional project financing structures designed only for big projects and deficiency in financing structures established for small projects are the most important economical disadvantages of alternative resources except the nuclear systems. Reviewing of such systems that conform to infrastructure investments requiring big budgets and consideration of environmental and approaching standards are a very complex process. This situation creates an irregular and ineffective competition environment with the conventional energy projects. Besides, the other negative situations are the first investments costs of alternative energy technologies are high and external costs are not considered in socio-environmental subjects. Especially, development possibility of fuel cells is seen in the highest risky group in respect to financial and marketing strategies. Though no risk is seen in the wind and photovoltaic transformation systems, especially in respect to research and development (R&D) activities, photovoltaic cells are involved in the high risky technologies group in respect to marketing and finance [11].

To eliminate such disadvantages, financing of package projects consist of different renewable energy projects can be ensured. Besides, development of very small-scale financing instruments, financing and investments provided from the private sector, guarantees of government and increasing of flexibility in financial structures contribute in elimination of economical obstacles [1,9,12].

4. Sustainability analysis

In this section, the sustainability parameters given above are examined under titles in respect to electric energy production systems.

4.1. The unit energy cost

It is one of the most important parameters in energy production. It may vary depending on various factors. Especially, the raw materials such as petroleum, natural gas and nuclear fuel are being continuously affected from economical conditions. The unit energy cost may increase to 1.2$/kW h in stand-alone photovoltaic systems. In the PV systems connected to network, it is in level compatible with all the other production technologies. The most advantageous system in respect to unit energy cost is the nuclear power stations. In these power stations, energy production costs 1.72–2.73 cents/kW h. The production systems with coal and natural gas have a unit energy cost below 0.1$/kW h. Though fuel cell technologies develop rapidly, the unit energy cost is about 0.4–0.5$ per kW h. The wind, hydroelectric and geothermal sourced production systems have similar unit energy cost [9,13,14]. Especially, in stand-alone small-scale power stations, the first investment cost and unit energy cost are higher than the systems connected to network. However, if these systems are used for purpose of decreasing dependency to the network, they may decrease the negative effects of fossil fuel systems [15].

4.2. Carbon dioxide emission

The carbon dioxide emission is in unacceptable levels especially for the coal and natural gas sourced production systems. The coal power stations emit 1000 g carbon dioxide per kW h and natural power stations emit about 500–600 g. The emission values of fuel cells are similar. In hydrogen production, generally natural gas is burnt with conventional method depended on methane steam reform and as this method is 10–100 times cheaper than the electrolysis systems made with PV or energy obtained from wind, it makes greater part of production [16]. In geothermal systems, this value may raise to 170 g/kW h. Other production systems generally have emission values below 1 g/kW h. 90% of emission in the photovoltaic and wind systems occurs during the production phase of PV panel and auxiliary elements. The emission amount that occurs in operation is about 2–3% [17]. This value may be neglected [18]. Though nuclear power stations have negative affects on environment because of their radioactive wastes, their CO_2 emission rates are close to the wind and solar systems [19]. In Fig. 2, the unit energy costs of electric energy production technologies and ranges of carbon dioxide emission amounts are given.

4.3. Availability

The energy resources such as petroleum and natural gas give unequal distribution in the world. 63% of the world's petroleum reserve is in the Middle East. According to the calculations made, the compensation period of consumption by production is about 80 years. The petroleum production will reach to its peak level and demonstrate a decreasing tendency in 2010 according to the pessimistic scenarios and 2035 according to the optimistic

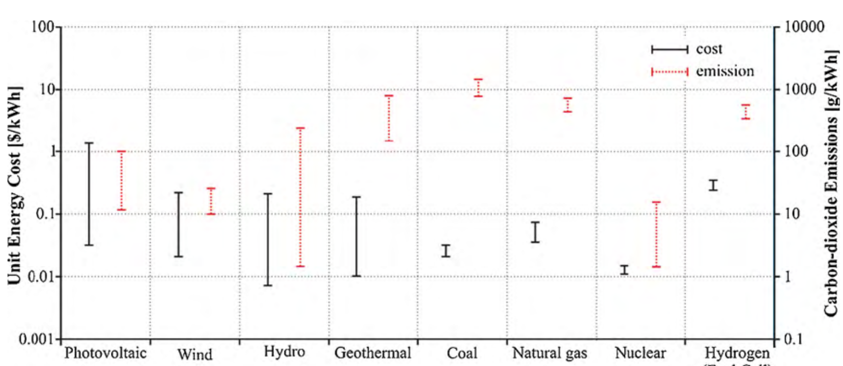


Fig. 2. Unit energy costs and CO_2 emissions of power generation systems.

sceneries. Similarly, 41% of the world's natural gas reserve is in the Middle East and 27% in the boundaries of Russia. It is forecast that the economical life of gas is 120 years as it is not consumed as much as petroleum. 50% of coal reserves remain within boundaries of only 3 countries (26% America, 16% Russia and 11.5% China). Compensation period of consumption by production is estimated as 185–260 years. Though it is forecast that the world's coal reserves are much more than the amounts known today, it is thought that most of them are low quality and difficult to obtain. It is forecast that economical life of uranium and thorium elements used in production of nuclear energy is about 280 years. However, as 99% of the determined reserves (2.85 million tons) remain in boundaries of only 10 countries, these resources are deemed as disadvantageous in respect to availability [20]. 439 nuclear power stations in all around the world produce 9.3 EJ energy per year. In the most optimistic scenario, it is forecast that the share of nuclear fueled electric energy production in total production will not increase until year of 2030 and even, it will decrease [21]. The renewable energy resources are classified as resources that always exist in the world and never consume. For this reason, they are very advantageous in respect to availability. For instance, the annual solar energy amount falling on earth is above 170,000 TW h. Similarly, the International Energy Agency determined the annual wind energy potential of the world as 40,000 TW h [22]. However, seasonal, daily and even momentarily changes in amounts of these two systems limit their usage as a basic power system. The hydroelectric power stations are the systems that have the highest availability, flexibility and reliability rates in the world. They can be commissioned within very short periods or their output power amount can be changed whenever it is desired. They are rather convenient to be used as both a basic and puant power plants. However, though the power amount that may be evaluated economically in the world exceeds 13,000 TW h, only 2600 TW h energy can be obtained [23,24]. Availability of geothermal energy resources depends on geographical limitations. 70% of the power in the European continent is within boundaries of only 6 countries and 33% of this installed power takes place in Sweden [25]. About 54 TW h/year electric energy in 24 countries is obtained from these resources. As it is available at every hour of a day, contrary to the wind and photovoltaic systems, they are convenient to be used as a basic power station [9].

4.4. Efficiency

Hydroelectric power stations are accepted as the most advantageous energy production technology in respect to energy output. In hydroelectric systems, fresh water loss does not occur except evaporation. Besides, no fuel consumption exits. For this reason, the output of synchronized generators that make energy transformation in the system is accepted as the approximate output and this value is mostly above 90%.

The efficiency of wind power stations may vary depending on geographical conditions in great range of 24–54%. The outputs of fuel cells, coal power stations and nuclear power stations generally remain in range of 30–45%. The natural gas power stations operate in output of 45–55%. The geothermal and photovoltaic systems are the energy transformation systems having the lowest output. Especially, in the photovoltaic systems, efficiency varies greatly depending on structure of the solar cell. The silicon solar cells holding the great part of the solar cell market have an output varying in range of 12–22% [9,17,26,27]. However, the output of these cells can reach to 27% with addition of concentrator systems [28]. The highest output obtainable for the solar cells is determined as 30–35%. However, the cell output can be increased to 66% theoretically by using the nanotechnology product materials [29]. In that case, development of solar cells with efficiency range of 40–50% in the near future seems realistic.

4.5. Fresh water consumption

The fresh water consumption of the energy production system is also an important sustainability indicator. However, to obtain that value correctly is very difficult especially for the renewable energy resources. Studies made in literature indicate that nuclear power stations are very disadvantageous in respect to fresh water consumption. Fresh water consumptions may increase from 30 kg to 100 kg per kW h depending on properties of the cooling technology. Hydroelectric power stations create a significant water loss of 65–70 kg per kW h because of evaporation. Natural gas and coal power stations consume 15–30 kg fresh water per kW h. Fuel cells consume fresh water below 2 kg/kW h and solar and hydroelectric power stations consume less than 1 kg. The water amount lost in production of photovoltaic module and wind tribunes can be considered as fresh water consumed by these two resources. The solar and wind power stations almost consume no water during operation are the most advantageous systems in respect to that indicator. Fresh water consumptions of geothermal systems are expressed with different values in various resources. For instance [9], resource gives the value of 12–300 kg/kW h for geothermal systems but it is below 2 kg according to the [30] resource. However, if we assume that the water generally used in these systems are returned to its source, the value of 2 kg/kW h seems more realistic. The comparative graphic of energy production systems in respect to output and fresh water consumptions are given in Fig. 3.

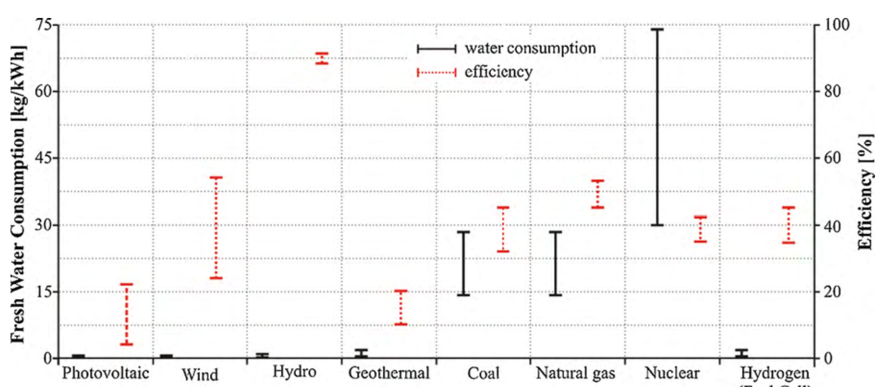


Fig. 3. Efficiency–fresh water consumption comparisons of power generation systems.

4.6. Land use

The other important sustainability indicator of the electric energy production systems is the land use. The land loss may be examined in very different aspects. Any accident to occur in nuclear power stations may affect thousands of km^2 area in a manner preventing its usage for many years. Hydroelectric systems also cause inevitable land destructions. Their negative affects on historical and natural structure of barrage lakes are known. Besides, petroleum leakages may cause he land and water pollutions with high cleaning costs.

In this study, land uses of energy production system per GW are examined. When the values of land use that is involved in the sustainability indicators are considered, the most advantageous systems are nuclear, natural gas and coal power stations that use fossil fuel. The nuclear and natural gas power stations have very advantageous land use values of 1–4 km^2/GW. This value increases in coal power stations because of some technical reasons. While this value is calculated as 28–64 km^2 per GW for the photovoltaic systems that is the most advantageous system in respect to land use among the renewable energy resources, it is calculated as 50–150 km^2 for the wind power stations. The climate conditions in these systems may change the rate of land use in significant levels like 20–40% [31,32]. The land use value in hydroelectric power stations may vary greatly depending on geographical characteristics of the region. In the literature, the land use value for such systems is given as 75–750 km^2 per GW. The land use value in geothermal systems is between 18 and 74 km^2/GW/GW [9,33]. The values given above show the areas covered by physical structure of the power system. Especially, when the areas used to take out raw materials in the coal and natural gas power stations that use fossil fuel are considered, it is seen that the renewable energy resources, mainly the photovoltaic systems, are more sustainable. In that situation, in comparisons of the coal power stations and PV system, it is forecast that energy produced by the PV system will be 40% more in average [34].

4.7. Social affects

Today, one of the most sustainability indicators of the energy resources is the social affects. The electric energy production technologies create important affects on social life of societies. Their direct and indirect risks on human health, air pollution, global warming and external costs that occur because of losses as a result of sudden accidents affect the point of view of societies on energy production technologies. It is very difficult to definitely determine monetary value of external costs. The environmental performance indicators determined by OECD in 1998 and sustainability development indicators established by the Nuclear Energy Agency in 2002 for the nuclear systems summarize the environment and human aspects of social costs.

Environmental indicators are divided into two groups; pollution and resource consumption. Climate changes, damages given to the ozone layer, air quality, wastes and changes in water quality are grouped under the concept of pollution. Water, forest, energy, mine and qualified land consumption and damage given to biological assortment are the components of environmental indicators. The employment potential established by the production technologies, manpower cost, working losses as a result of diseases and accidents resulting from these technologies, deaths, harmful effects exposed by employees and people around and similar indicators form the humanistic aspect [9,11,32].

The coal and petroleum sourced production technologies have the highest external cost figure. The unit cost of coal production gradually decreases. However, difficulty in production process and its negative affects on human health cause decrease in employment made on that area in many countries. Besides, it is widely expected that coal depended production technologies will be abandoned as a result of developing economical structure and liberalization or it will face to very important changes [35]. The natural gas systems have the lowest external cost figure among the fossil fuels. The environmental affects of natural gas power stations are similar to photovoltaic systems. The nuclear power stations are the energy production systems having the lowest social affect. However, because of the negative perception created by the Chernobyl disaster, it is the mostly argued and least accepted electric energy production technology. But it is seen among the sustainable energy resources of the 21st century by the science environment. The reason of it is that availability of raw materials and they are not affected from the climate conditions like solar and wind power stations [36]. In general, renewable energy technologies are the most advantageous systems in respect to labor force and employment. Besides, their negative affects on environment are very less. Especially for countries that do not have rich resources in respect to fossil fuel, the price fluctuations of the produced energy may be reduced to minimum level by decreasing dependency on such fuels. The photovoltaic systems do not cause any noise pollution as they operate silently. Though they receive some negative reactions because of combustible, explosive and toxicological matters used during the module production, by using the thin film technology, consumption of such matters may be greatly decreased. Especially, the silicon contented cells almost have no harmful effect on environment during their nominal operation. But, in Copper–Indium–Diselenide (CIS) and Cadmium Tellurium (CdTe) contented cells, small amount of poisonous matters are being used. In case of fire or defect, emission of such matters in environment may be risky. In addition to thin film technologies, with studies made to increase the energy consumed per unit land by using focusing systems, use more secure and productive materials during production phase and develop recycling systems of cells, it is aimed to minimize the environmental affects [37]. The most important disadvantages of wind power stations are the noise and visual pollution and the damages they give to natural life of birds. The odor and noise pollution of geothermal systems and their possibility to affect the seismic activities are the important social effects. These problems may be decreased by injecting the fluid used with the closed cycle transformation systems into the underground. Especially, acceptability of big powered hydroelectric systems by the society has gradually decreased in recent years because of the widespread perception on negative effects of barrage lakes on climate, living organisms and human communities and the harm they give to historical and natural beauties. However, the opportunities provided by hydroelectric systems in various social areas like agriculture, water sports and tourism increase their sustainability advantage [9,38]. The sole production system among the fossil fueled power stations largely accepted by the society is the natural gas power stations. They do not cause air pollution, their wastes are very less and they can be installed and commissioned in a very short time, and these facts increase their social sustainability.

As the fuel cells use hydrogen produced by natural gas reform, they have the similar characteristics. However, the most important disadvantages of these systems are they are not known by the society sufficiently, they are perceived as a production method using fossil fuel and their storing and transportation systems create visual pollution. To benefit from hydrogen as an energy conveyor, it must be obtained by using renewable energy resources in long term. The simplest method of obtaining clean hydrogen is electrolyzes of water. Studies on obtaining hydrogen by using photolysis, biochemical and thermo

Table 1
Sustainability analysis of electrical energy production systems.

Technology	Unit energy cost	CO_2 emissions	Availability	Efficiency	Fresh water consumption	Land use	Social influences		Total	Sustainability order
							External costs	External benefits		
Coal	2	8	5	5	7	3	8	7	45	8
Natural gas	3	7	6	2	6	2	6	6	38	6
Nuclear	1	1	8	3	8	1	1	8	31	2
Hydrogen (fuel cell)	7	6	7	4	4	4	5	5	42	7
Photovoltaic	8	3	1	8	2	5	4	2	33	4
Wind	6	2	2	6	1	8	3	1	29	1
Geothermal	5	5	4	7	5	6	2	4	38	5
Hydroelectric	4	4	3	1	3	7	7	3	32	3

chemical methods gradually gain speed. The most important disadvantage of these systems is their high cost production. Besides, high light energy loss, output insufficiency of biochemical processes and harm given to algae and useful bacteria are the other disadvantages of photolysis. Studies are being carried out in molecular biology and physiology to decrease such disadvantages [39]. It is forecast that hydrogen will have the highest sustainability rate in long-term except its fresh water consumption during its production [38,40]. In long-term forecasts containing various scenarios made by the World Energy Council, hydrogen is assumed as a sustainable energy resource to be used in significant amount at the end of this century [41]. In short-term, a transition period will appear and hydrogen production in great amounts will be ensured with development and optimization of existing technologies [42].

Especially, sustainability of alternative energy resources in respect to social perception may be increased by means of various measures such as introduction activities to ensure recognition by the society, raising awareness of the public by means of education, explanation of all the technology related information to the public opinion, determination of innovative energy production strategies and establishment of tracing and evaluation mechanisms [43].

5. Conclusions

In this study, the renewable energy resources such as wind, sun, hydrothermal and geothermal resources, fossil fueled coal and natural gas power stations, nuclear power stations and fuel cells are examined in respect to sustainability criteria. Alignment of energy production technologies is made according to the average values for each indicator and is given in Table 1.

In general, it is determined that the renewable energy resources are sustainable technologies more than others. The wind power stations having the highest rank sustainability are followed by the nuclear and hydroelectric power stations. The photovoltaic cells are in the 4th order according to the data of today. However, in long-term forecasts made by the World Energy Council, it is determined that 60% of the electric energy production will be covered from photovoltaic systems at the end of this century [44]. For this reason, the photovoltaic systems will be the preferential technologies in long term as a result of developments made in semi conductive technology and using of nanomaterials. The geothermal systems are the most disadvantageous renewable energy technology in respect to sustainability because of difficulty in their availability. The natural gas and fuel cell technologies have similar sustainability characters. If hydrogen used in fuel cells can be obtained from the renewable energy resources instead of natural gas, its sustainability alignment can be carried upwards. It is forecast that coal use in electric energy production will be abandoned completely in 2050s. The coal power stations have the lowest sustainability alignment among the technologies examined in this study.

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